the corresponding C / (N−I) is not less than the minimum 7.7 dB. the discrimination of the Earth-station antenna should be not less than 20.3 dB. To achieve that amount of isolation the interfering SPACEWAY satellite must be not less than **0.92°** off the boresite of that antenna. (See Section D.5.2.2 of Annex D for detailed consideration of this separation.) The actual required separations between IRIDIUM Earth stations to meet this requirement depend as before on the elevation angle of the GSO satellite. At a 30° elevation angle, the minimum elevation angle of SPACEWAY Earth stations in CONUS, the required separation varies between 25 km and 50 km, or **between 13.5 and 27 nautical miles**, depending on the angle between a line joining the two IRIDIUM Earth stations involved and a line between one of these Earth stations and the GSO satellite. These required separation distances are considerably smaller than the 37 nautical mile separation between IRIDIUM Earth stations as planned (see Figure 1). The obvious conclusion is that IRIDIUM Earth station diversity can be used successfully to eliminate downlink interference into the IRIDIUM system from the SPACEWAY system even if APC is not used in a complementary way to reduce the magnitude of that interference. The required Earth-station separation distances are significantly smaller when downlink APC is also used, but if the Earth stations were placed at 37 nautical mile separations for other reasons the use of downlink APC in the IRIDIUM spacecraft would be unnecessary.

3.3   Summary of Findings

The results discussed in the above two sections 3.1 and 3.2, and in more detail in Annex D, are summarized in the following table:

Table 1

**Required Separation Angles and Distances Between Earth Stations
Used in an Interference - Mitigation Process
To Reduce Worst-Case Interference to Acceptable Levels**

Interfered-with Link	When IRIDIUM APC Is Used		When IRIDIUM APC Is Not Used	
	Angle	Distance, NM	Angle	Distance, NM
IRIDIUM Uplink	0°	0	≥ 27°	≥ 455
SPACEWAY Uplink	0.313°	4.6 to 9.2	0°	0
IRIDIUM Downlink	0.243°	3.6 to 7.2	0.92°	13.5 to 27
SPACEWAY Downlink	0.316°	4.65 to 9.3	0°	0

Given that the current design of an IRIDIUM Earth station complex includes a central Earth station and two peripheral Earth stations, each 37 NM from the central Earth station and 68 NM from each

other, these required distances in Table 1 are quite feasible, except of course for the requirement to accommodate IRIDIUM uplinks when APC is not used in the IRIDIUM Earth stations.

The immediate conclusions to be drawn from these findings are that

1. When APC is used at the IRIDIUM Earth stations (uplink APC) and in the IRIDIUM spacecraft (downlink APC) as an interference-mitigation measure, the required separation distances of alternate IRIDIUM Earth stations to carry out a complementary Earth-station-diversity interference-mitigation measure are quite modest, all much less than the distances between the same Earth stations for other reasons.

2. When APC in the IRIDIUM system is not used as an interference-mitigation measure, but rather is held in reserve purely to overcome propagation attenuation affects and changes in free-space loss as the IRIDIUM Earth-station elevation angle changes, Earth-station-diversity can still be used successfully as an interference-mitigation measure to eliminate harmful interference in the downlink of the IRIDIUM system, but not in the uplink.

3. Based on conclusions (1) and (2) above, interference between the SPACEWAY and IRIDIUM systems can be avoided by a combination of using the existing IRIDIUM Earth stations in an interference-mitigation manner, combined with the use of up to 25 dB of the 30.7 dB of available APC in the IRIDIUM Earth stations to combat uplink interference into the IRIDIUM system. Use of downlink APC in the IRIDIUM spacecraft would ease the problem of avoiding downlink interference into the IRIDIUM system, but the interference can successfully avoided in the downlink by the application of Earth-station diversity alone from antennas at sites planned for other reasons.

4. **Discussion of Results**

The results described in Section 3, summarized in Table 1, indicate definitely that IRIDIUM Earth station diversity is an effective interference-mitigation technique when combined with the use of reserve APC transmitter power to overcome interference into the IRIDIUM system. Use of APC power in the IRIDIUM spacecraft is an added optional technique that eases the requirements of the Earth-station-diversity technique in the downlink, but if necessary the available diversity in Earth station locations can overcome downlink interference without the use of spacecraft APC.

This section discusses briefly a number of matters stemming from these results. They include:

*   the predictability of when an alternate IRIDIUM Earth station should be used to avoid interference;

* the potential for using Earth station diversity in the SPACEWAY system instead of or as a complement to Earth station diversity in the IRIDIUM system;

* the possibility of using APC in the SPACEWAY system rather than in the IRIDIUM system;

* the relative advantages of Earth-station diversity and of the space-station diversity technique described earlier in Reference (1); and

* the implications of the above results on the general question of the sharing of spectrum between GSO fixed-satellite systems and feeder-links of non-GSO mobile-satellite systems.

4.1 The Predictability of When an Alternate IRIDIUM Earth Station Should Be Used to Avoid Interference

The above text considers the possibility of using an alternate IRIDIUM Earth station when use of the primary Earth station would result in interference into either the IRIDIUM network or the SPACEWAY network, or both. It was concluded above that this technique could be used to avoid harmful interference between the two networks, and that the required distances between the different IRIDIUM Earth stations was quite feasible. What was not discussed was how to implement a system to carry out this diversity technique, and how to determine when to put the technique into effect. The first of these two subjects is considered outside of the terms of reference of the current study, but the second is addressed here.

The switch-over from one Earth station to another, or perhaps the choice of which of three Earth stations in the IRIDIUM Earth-station complex to be used in a given pass of an IRIDIUM satellite, would have to be done by personnel operating the IRIDIUM network. The exact locations and orbits of the 66 IRIDIUM satellites are known at all times by the IRIDIUM operational staff, aided by whatever computer tools are required. As well, the locations of the GSO satellites are known, within their station-keeping tolerances. From this combined body of information the exact time of a potential interference event can be predicted, and which of the three IRIDIUM Earth stations is located such that it would be involved. The simplest procedure for the IRIDIUM operator at the Earth station complex would be to not use that particular Earth station antenna on that particular pass. Alternatively, if necessary, the same Earth-station switch-over techniques could be used that are presumably implemented to handle unpredictable needs to switch Earth stations in the event of a heavy local rain.

It may be necessary to add the station-keeping tolerance of the GSO spacecraft to the required angles determined in the above analysis if a prediction technique is used to determine when an alternate Earth station has to be used, but these angles are in the order of 0.05°, and could be absorbed into the angles indicated in Table 1 without exceeding the distances between planned IRIDIUM Earth station antennas.

4.2   The Potential for Using Earth Station Diversity in the SPACEWAY System Instead of or as a Complement to Earth Station Diversity in the IRIDIUM System

The above analysis and discussion has concentrated on the possibility of using diversity in choice of IRIDIUM Earth station as an interference-mitigation tool. However, the general equations developed in Section D.3 of Annex D suggest that any one of the antennas in either the SPACEWAY or the IRIDIUM systems could theoretically be used for interference mitigation. It was shown in Section D.5.2.1 that use of the IRIDIUM spacecraft antenna is not an effective interference-mitigation technique. The same applies to use of the SPACEWAY spacecraft antenna.

Use of the SPACEWAY Earth-station antennas is similarly not an effective technique. for the following reasons:

1.   The beamwidths of the SPACEWAY Earth terminals are considerably greater than that of the IRIDIUM Earth stations, 1.1° in the uplink and 1.6° in the downlink in the present analysis, and possibly as large as 3° in other applications, in contrast to 0.24° in the uplink and 0.36° in the downlink of the IRIDIUM system. The necessary separation distances between Earth stations to carry out a successful Earth-station-diversity measure is directly proportional to the antenna beamwidth. Thus distances about 4.6 times as far would be required if SPACEWAY Earth terminals were used, in the order of 21 to 43 nautical miles instead of the required 4.6 to 9.3 nautical mile separations of IRIDIUM Earth station antennas.

2.   There are large numbers of these small user-operated Earth terminals planned as part of the SPACEWAY network. The costs and operational difficulties of having alternate Earth terminals for these small terminals would be incomparably greater than using alternative Earth stations in the IRIDIUM system, when these alternate Earth stations are already installed and operational for a different reason.

3.   The users of the SPACEWAY system would not have access to the information base nor the computer capability to know precisely when to implement the alternate Earth station, assuming that it were installed and ready to be used on command.

Thus it is concluded that the only antennas that can be used as interference-mitigation tools are the Earth station antennas of the IRIDIUM system

4.3   The Possibility of Using APC in the SPACEWAY System Rather than in the IRIDIUM System

The above analysis considered the advantages of using APC in the IRIDIUM system as a complement to the Earth-station-diversity technique to reduce the interference between the networks

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to acceptable levels. It was shown that while Earth-station diversity alone is adequate in the downlink, the use of APC is also required in the uplink to protect the IRIDIUM system. The question arising naturally from this finding is:

> *Is there a way to use APC in the SPACEWAY system to reduce interference between the two networks, if it were available ?*

The answer is short and simple: **no**. The reason for this answer is more complex, as follows:

> APC in the IRIDIUM system is effective in reducing the interference between the two networks primarily because without utilizing the extra transmitter power in that system, the lower power IRIDIUM system receives harmful interference, but the interference that it inflicts on the SPACEWAY system does not result in harmful interference in that network. When IRIDIUM APC is applied the SPACEWAY system becomes the interfered-with network, in both uplink and downlink, rather than the interfering network. The change is more than simply a change in roles, however, because of the presence of the high-gain IRIDIUM Earth-station antennas. Without any further action, the availability of the interfered-with SPACEWAY network is much greater than the availability of the IRIDIUM network before the application of APC in that network. Further, when the IRIDIUM Earth stations assume the role of interferer, Earth-station-diversity of those same high-gain Earth station antennas becomes an effective interference-mitigation tool.

> Using additional APC power that is presumably available in the SPACEWAY system, presumably to combat rain attenuation, would only lessen the effectiveness of the use of the additional APC power in the IRIDIUM system. There is no combination of raw EIRP values in the two systems that can be applied to overcome interference in the two networks without the application of other techniques as well. Those other techniques would not be aided, and in part would be negated, by the application of APC power in the SPACEWAY system to overcome interference. Such action would be a win-lose activity rather than a win-win activity.

4.4   The Relative Advantages of Earth-station Diversity and of the Space-Station Diversity Technique Described Earlier in Reference (1)

The Earth-station diversity technique has been described in detail in this report. The aspect of that technique that is considered here is the required separation in Earth stations to meet a given separation angle between the non-GSO IRIDIUM satellite and the GSO SPACEWAY satellite. That distance varies at least inversely as the Sine of the elevation angle of the GSO satellite at the IRIDIUM Earth station, and perhaps inversely as the square of the Sine of that angle if the relative locations of the IRIDIUM Earth station antennas are bad in relation to the direction of the GSO satellite, as described by Equation (1) above. In either case, the technique is less applicable at

high latitude locations such as parts of Canada, where high elevation angles are simply unavailable.

Fortunately, in these same high latitude service areas the technique of using an alternate IRIDIUM satellite to avoid interference is most applicable, as described in Reference 1. Specifically, if the latitude of the IRIDIUM Earth station is greater than about 50° a second IRIDIUM satellite can be seen at an elevation angle of greater than 10°. In general, the technique of avoiding harmful interference by using alternate IRIDIUM Earth station is applicable at low to medium latitudes, and the technique of using an alternate IRIDIUM satellite is applicable at medium to high latitudes; the two techniques are complementary. Further, the choice of using one or the other technique can be decided independently for each IRIDIUM Earth station. The only constraining factor in this arrangement is that if the alternate-satellite technique is used the traffic in the IRIDIUM network has to be re-routed accordingly.

4.5 The Implications of the Above Results on the General Question of the Sharing of Spectrum Between GSO Fixed-Satellite Systems and Feeder-Links of Non-GSO Mobile-Satellite Systems

The above results can be generalized in a number of ways, and these generalizations can and should have an effect on the rules by which the spectrum allocated to the fixed-satellite service is utilized.

The first generalization is that the above Earth-station-diversity results can be generalized to apply to the sharing between the IRIDIUM system and a large class of geostationary fixed-satellite networks. To be effective, the IRIDIUM system should, either before or after the use of APC, be the interferer network rather than the interfered-with network. This is particularly necessary in the uplink. Such a condition would apply to all practical Ka-band GSO networks with an uplink EIRP spectral density as great as about 6 dB greater than that in the SPACEWAY system. Once that condition is met, IRIDIUM Earth station diversity can be applied to ovoid instances of harmful interference. If the latitude of the GSO service area and of the IRIDIUM Earth station is such that low elevation angles are necessary, then the technique of using an alternate IRIDIUM satellite can be utilized.

Generalizing now to the feeder links of different non-GSO mobile-satellite systems, the application of the Earth-station-diversity technique requires only that the non-GSO feeder-link system have sufficiently high transmitter-power levels in the uplink, with or without the use of APC, to be the interfering system rather than the interfered-with system. With that condition, and the availability of an alternate Earth station or stations in an Earth-station complex, the technique can be used to avoid interference. The angles involved make the technique practical for non-GSO mobile-satellite networks in low Earth orbit, under say 1,000 km, but would be less practical in the sharing between GSO networks and higher non-GSO systems in orbits of say 10,000 km such as ODYSSEY. Note that if the above conditions are met there is no constraint placed on the characteristics of the antenna patterns of either GSO or non-GSO network.

If the above technique is to be used at high latitudes to the extent that the Sin^{-2} (θ) factor is a problem, the alternate-satellite technique can only be applied successfully if either the service links would also switch to the alternate satellite or that the MSS system employed inter-satellite links as the IRIDIUM system does.

Generalizing now to other frequency bands, the alternate-Earth-station interference-mitigation technique is applicable to any non-GSO system in LEO orbit, but would be less effective if the MSS system were in ICO orbit in the 10,000 km altitude range. The Earth-station complex of the MSS system would of course have to have two or three antennas separated by distances measured in the tens of miles. Such a complex may not be required at lower frequencies to combat rain attenuation, and if not would be a direct cost of avoiding interference events involving GSO satellite networks sharing the band.

5.   Conclusions

The first conclusion reached is that the technique of using an alternate IRIDIUM Earth station within the IRIDIUM Earth-station complex is a powerful and practical way to avoid interference events between that system and the GSO SPACEWAY system. Application of the technique would not require any major additions to the hardware of the IRIDIUM system, but only software changes involving the operation of APC systems and the choice of Earth station within an Earth-station complex. At higher latitudes, if sharing of the spectrum involved the sharing with GSO satellites with such low elevation angles that the required Earth-station separations were greater than that implemented in construction of that Earth-station complex, the technique of choosing an alternate IRIDIUM satellite could be used instead.

These results., which relate to the sharing of spectrum between two specific satellite systems, can be and are generalized in a number of ways. These generalizations can and should be the basis for ITU Regulations and Recommendations on the sharing of spectrum between GSO and non-GSO networks.

6.   References

1.   Robert Bowen Associates Ltd., " Analysis of the Feasibility of Sharing Co-Directional Use of the Fixed-Satellite 19 GHz Downlink and 29 GHz Uplink Bands Between the Geostationary Spaceway Fixed-Satellite System and Feeder Links of the Iridium LEO Mobile-Satellite System", a report to Hughes Space and Communications Company, March 8, 1995.

Annex A

System Characteristics
Used in Interference Analysis
Between Spaceway and Iridium Systems

A.1: Introduction

Characteristics of the SPACEWAY and IRIDIUM systems are noted in this annex. These characteristics were obtained from Hughes Space & Communications Company (Hughes) on January 23, 1995. The characteristics are used in analyses of the link budgets of the SPACEWAY and IRIDIUM systems, and the information obtained in those analyses are in turn used in the analysis of interference between the two systems. Thus the data listed in this annex is the data-base for the analysis in the complete report. Changes in numerical values of the quantities discussed in this annex would not necessarily affect the analysis procedure, but would affect the numerical values of the results obtained, and so might affect the conclusions drawn.

A.2: Characteristics of the Iridium System

A.2.1 Iridium Uplink Characteristics:

Iridium Uplink System Characteristics:

Modulation:	QPSK / 6.250 Mbps raw data rate, 3.125 Mbps information rate
Bandwidth:	6.250 MHz (one bit per Hz before a 2:1 coding redundancy)
Polarization:	Right-hand circular
C/(N+I), rain	7.8 dB
C/(N+I), clear	10.7 dB
Req'd. C/(N+I)	7.7 dB, assumed to be a separate requirement for uplink and downlink independently, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path. For Iridium the bit-rate and signal bandwidth are equal, and so $E_b / N_o = C / N$.

Iridium Uplink Satellite Characteristics:

Min. Elev. Angle:	5°
Satellite Altitude:	780 km.
Sat. Noise Temp.	1,295 ° K
Sat. Ant. Gain:	30.1 dBi, 5 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	4 independent steerable spot beams per spacecraft

Iridium Uplink Earth Station Characteristics:

ES Antenna Gain:	56.3 dBi, 0.24° beamwidth, steerable
Xmtr. Power:	-22.3 dBW to + 12 dBW, APC capability over the 34.3 dB range, designed to overcome range and atmospheric losses, to keep constant Eb/(No + Io) at the receiver's antenna input

A.2.2 Iridium Downlink Characteristics:

Iridium Downlink System Characteristics: (same as for the uplink):

Modulation:	QPSK / 6.250 Mbps raw data rate, 3.125 Mbps information rate
Bandwidth:	6.250 MHz (one bit per Hz before a 2:1 coding redundancy)
Polarization:	Right-hand circular
C/(N+I), rain	7.8 dB
C/(N+I), clear	10.7 dB
Req'd. C/(N+I)	7.7 dB, assumed to be a separate requirement for uplink and downlink independently, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path. For Iridium the bit-rate and signal bandwidth are equal, and so for Iridium

$$E_b / N_o = C / N.$$

Iridium Downlink Earth Station Characteristics:

ES Antenna Gain:	53.2 dBi, 0.36° beamwidth, steerable
Noise Temp.	731° K

Iridium Downlink Satellite Characteristics:

Satellite Altitude:	780 km.
Sat. Ant. Gain:	26.9 dBi, 7.4 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	4 independent steerable spot beams per spacecraft
Xmtr. Power:	-22.4 dBW to -3.2 dBW, APC capability over the 19.2 dB range, designed to overcome range and atmospheric losses, to keep constant Eb/(No + Io) at the receiver's antenna input

A.3: Characteristics of the Spaceway System

A.3.1 Spaceway Uplink Characteristics:

Spaceway Uplink System Characteristics:

Modulation:	QPSK / 1544, 768, 384 kbps
Access:	FDMA
Bandwidth:	2 MHz, 1 MHz, or 0.500 MHz, (0.77 bits per Hz)
Polarization:	Circular
$E_b/(N_o)$, rain	9.7 dB
C / N, rain	8.6 dB, reduced from $E_b / (N_o)$ by 1.1 dB
$E_b/(N_o)$, clear	11.7 dB
C / N, clear	10.6 dB, reduced from $E_b / (N_o)$ by 1.1 dB
Req'd $E_b/(N_o + I_o)$	8.0 dB, and
Req'd. C/(N+I)	6.9 dB, reduced from $E_b/(N_o)$ by 1.1 dB, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path.

Spaceway Uplink Earth Station Characteristics:

ES Antenna Gain:	44.3 dBi, 1.1° beamwidth, not steerable
Xmtr. Power:	-3.5 dBW for the 384 kbps carrier

Spaceway Uplink Satellite Characteristics:

Min. Elev. Angle:	30 °
Satellite Altitude:	GSO.
Sat. Noise Temp.	575 ° K
Sat. Ant. Gain:	46.5 dBi, 1 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	multiple simultaneously-used spot beams per spacecraft, not steerable

A.3.2 Spaceway Downlink Characteristics:

Spaceway Downlink System Characteristics :

Modulation:	QPSK / 92 Mbps
Bandwidth:	120 MHz (0.77 bit per Hz)
Polarization:	Circular
$E_b/(N_o + I_o)$, rain	5.7 dB
C/(N+I), rain	4.6 dB, reduced from $E_b/(N_o)$ by 1.1 dB
$E_b/(N_o + I_o)$, clear	17.9 dB
C/(N+I), clear	16.8 dB, reduced from $E_b/(N_o)$ by 1.1 dB
Req'd. $E_b/(N_o + I_o)$	5.0 dB, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path,
Req'd. C/(N+I)	3.9 dB, reduced from $E_b/(N_o)$ by 1.1 dB, with re-modulation in spacecraft such that bit errors, not noise powers, add in considering total signal path.

Spaceway Downlink Earth Station Characteristics:

ES Antenna Gain:	43.1 dBi, 1.6° beamwidth, not steerable
Noise Temp.	275 ° K

Spaceway Downlink Satellite Characteristics:

Min. Elev. Angle:	30 °
Satellite Altitude:	GSO.
Sat. Ant. Gain:	46.5 dBi, 1.1 ° beamwidth, sidelobes as per App.29 Ann. III
Sat. Ant. Char.	multiple simultaneously-used spot beams per spacecraft, not steerable
Xmtr. Power:	12.5 dBW

Annex B

Noise Budgets of the IRIDIUM and SPACEWAY Systems

B.1   Introduction

The noise budgets of the IRIDIUM and SPACEWAY systems are analyzed in this annex, based primarily on information available in Annex A of this report. This analysis is done primarily to provide the necessary input data for an analysis of the interference between the two systems. Particular attention is paid to the automatic power control (APC) of the Iridium system, as its use is important in determining the interference between the two systems, as is discussed in the main report and in Annex C to follow. In this consideration of the Iridium APC system no account is taken of the quantization of the APC steps nor of inaccuracies in the APC servo system.

B.2.   IRIDIUM System Noise Budgets

B.1.1   The IRIDIUM Uplink Noise Budget

The Iridium uplink noise budget is a function of the elevation angle of the Iridium spacecraft. Elevation angles of 90° (zenith) , 30°, and 5° are considered here. 30° is important because it is the minimum operational angle of the Spaceway system, and 5° because it is the minimum operational angle of the Iridium system. The Iridium uplink parameters are indicated in Table B-1, using the standard satellite link equations. The clear-air attenuation is determined from formulae in CCIR Report 564-4 (1990). Simplified high-angle formulae of that report are used, because we are particularly interested in the budgets in the elevation angle range near 30 °.

B.1.2   The IRIDIUM Downlink Noise Budget

The same process is repeated for the Iridium downlink, concentrating on elevation angles of 90° (zenith) , 30°, and 5°. The Iridium downlink parameters are indicated in Table B-2. There seems to be some lack of rain-attenuation margin or even clear-air-attenuation margin in the Iridium downlink budget at low elevation angles, but this is not of particular concern as the interference events will occur at elevation angles of 30° and greater. Further, the low margins may be because of the use of multiple earth stations and the placement of earth-station complexes in dry climatic locations. In any case, these numbers affect the present study only to the extent that they relate to the understanding of the operation of the Iridium APC system in an interference environment.

B.2   The Spaceway Noise Budgets

There may be a "coals-to-Newcastle" aspect to deriving the Spaceway noise budget for Hughes, but it is a necessary step in the process, since parameter values determined in deriving the Spaceway noise budget are used in the interference analysis of the two systems. The budgets are simpler than those of the Iridium systems, as there is no wide variance in system elevation angles, nor is there use of APC in the many small user earth terminals as there is in the large Iridium feeder link earth stations.

The uplink budget of the Spaceway system is indicated in Table B-3, and the downlink budget is in Table B-4.

Table B-1
Uplink Noise Budgets of the Iridium System
at Spacecraft Elevation Angles 90 °, 30 °, and 5 °

Satellite Elevation Angle	90°	30°	5°
Carrier Frequency, GHz	29.3	29.3	29.3
Satellite Noise Temperature, Degrees K	1,295	1,295	1,295
Signal Bandwidth, MHz	6.25	6.25	6.25
Channel Separation, MHz	7.67	7.67	7.67
Noise Power, dBW	-129.5	-129.5	-129.5
Req'd. Clear Air C = N + 10.7 dBW	-118.8	-118.8	-118.8
Path Length, km.	780	1,560	8,950
Free Space Loss, dB	179.7	185.7	200.9
Earth Station Antenna Gain, dBi	56.3	56.3	56.3
Space Station Antenna Gain, dBi	30.1	30.1	30.1
Clear Air Attenuation, dB	0.41	0.83	4.76
Tx Power in dBW to provide C/N = 10.7 dB	-25.1	-18.7	+0.5
Margin of APC Tx. with Pmax = +12 dBW	37.1	30.7	11.5

Table B-2
Downlink Noise Budgets of the Iridium System
at Spacecraft Elevation Angles 90 °, 30 °, and 5 °

Satellite Elevation Angle	90°	30°	5°
Carrier Frequency, GHz	19.6	19.6	19.6
Earth Stat'n Noise Temperature, Degrees K	731	731	731
Signal Bandwidth, MHz	6.25	6.25	6.25
Channel Separation, MHz	7.22	7.22	7.22
Noise Power, dBW	-132.0	-132.0	-132.0
Req'd. Clear Air C = N + 10.7 dBW	-121.3	-121.3	-121.3
Path Length, km.	780	1,560	8,950
Free Space Loss, dB	176.2	182.2	197.4
Earth Station Antenna Gain, dBi	53.2	53.2	53.2
Space Station Antenna Gain, dBi	26.9	26.9	26.9
Clear Air Attenuation, dB	0.43	0.85	4.88
Tx Power in dBW to provide C/N = 10.7 dB	-24.8	-18.3	+ 0.9
Margin of APC Tx. with Pmax = - 3.2 dBW	21.6	15.1	?

? There does at first glance not seem to be enough margin in the IRIDIUM link budget to overcome the clear-air margin at very low elevation angles. That is probably, however, because the IRIDIUM earth stations are built in dry climates, and a fairly damp 15 g/m^3 water vapour concentration was assumed, that of the US south-east during winter. In any case, the interference analysis is done at 30 ° elevation angle, where this does not apply.

Table B-3
Uplink Noise Budget of the Spaceway System
at a Spacecraft Elevation Angle of 30 °

Carrier Frequency, GHz	29.3
Satellite Noise Temperature, Degrees K	575
Signal Bandwidth, kHz	500
Channel Separation, kHz	500
Noise Power, dBW	-144.01
Req'd. Clear Air C = N + 10.6 dBW	-133.41
Path Length, km.	39,230
Free Space Loss, dB	213.7
Earth Station Antenna Gain, dBi	44.3
Space Station Antenna Gain, dBi	46.5
Clear Air Attenuation, dB	0.8
Tx Power in dBW to provide C/N = 10.6 dB	-9.7
Margin of Tx. with P = -3.5 dBW	6.2

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Table B-4
Downlink Noise Budget of the Spaceway System
at a Spacecraft Elevation Angle of 30 °

Carrier Frequency, GHz	19.6
Satellite Noise Temperature, Degrees K	275
Signal Bandwidth, MHz	120
Channel Separation, MHz	120
Noise Power, dBW	-123.4
Req'd. Clear Air C = N + 16.8 dBW	-106.6
Path Length, km.	39,230
Free Space Loss, dB	210.2
Earth Station Antenna Gain, dBi	43.1
Space Station Antenna Gain. dBi	46.5
Clear Air Attenuation, dB	0.8
Tx Power in dBW to provide C/N = 16.8 dB	+ 14.8
Downlink Xmtr. Power, dBW	+ 12.5
Actual Clear-Air C, dBW	- 108.9
Actual Clear-Air C/N, dB	14.5 *

*   This may be due to the difference between performance in the centre of the SPACEWAY
service area and performance near the edge of the service area where the elevation angle is
30 °.

Annex C

Worst-Case Interference Analyses

C.1   Introduction

"Worst-case" interference analysis is determined in this annex. "Worst-case interference analysis" is the analysis of interference into each of the systems in the worst-case situation, ie. in the situation in which the earth terminal involved is pointed directly at both the GSO SPACEWAY satellite and the LEO IRIDIUM satellite. This is a transient situation, in that the LEO satellite is only in the main beam of the GSO earth station antenna for a short period of time, and visa-versa. The transient nature of the interference is discussed elsewhere in the report; in this annex only the peak interference levels of the transient interference burst are determined.

These peak transient interference levels are determined for four distinct interference situations:

1.   interference from the GSO earth station into the LEO satellite;
2.   interference from the LEO earth station into the GSO satellite;
3.   interference from the GSO satellite into the LEO earth station; and
4.   interference from the LEO satellite into the GSO earth station.

The analysis is done at a location where the elevation angles to the satellites is 30°, the minimum planned elevation angle of the SPACEWAY system. 384 kbps digital traffic is assumed in the SPACEWAY system from the user terminals.

C.2   Interference Ratios and the Equations Specifying their Magnitudes

In this analysis the pre-detection carrier-to-interference ratios C / I are determined. These C / I ratios are related to the post-detection E_b / N_o ratios and so BER ratios by the differences in dB between C / I and E_b / N_o specified in the information contained in Annex A. The "minimum" C/(N+I) values specified in Annex A are considered to be interference thresholds; interference margins are determined by whether the interference is more or less than the values specified by those thresholds.

The interference equations in an uplink-interference situation are:

$$C = P_D - A_{CA} - A_{FS} + G_{DES} + G_{SC} \quad\text{...} \quad (C.1),$$

$$I = P_I - A_{CA} - A_{FS} + G_{IES} + G_{SC} \quad\text{...} \quad (C.2),$$

and

$$C/I = (P_D - P_I) + (G_{DES} - G_{IES}) + F_{BW} \quad\text{...} \quad (C.3),$$

where C   is the desired carrier level at the interfered-with satellite,

P_D is the Xmtr power level of the desired carrier,

A_{CA} is the clear-air attenuation level in the transmission path,

A_{FS} is the free-space loss in the transmission path to the interfered-with satellite,

G_{DES} is the earth-station gain of the desired signal,

G_{SC} is the satellite-antenna gain of the interfered-with satellite,

I   is the interfering carrier level at the interfered-with satellite,

P_I is the Xmtr power level of the interfering carrier,

G_{IES} is the earth-station gain of the interfering signal, and

F_{BW} is a factor to account for the different bandwidths of the desired and interfering carriers.

It should be noted that in Eq'n (C.3) the terms A_{CA}, A_{FS}, and G_{SC} are not present, since they are common to the paths of the desired and the interfering carrier. (The desired and interfering earth stations are assumed to be at roughly the same location, relative to the distances of either of the two satellites.

Another point to clarify is that the interference is determined in clear-air propagation conditions; no account is taken of rain attenuation in these calculations. This is because a rain event and an interference event are each independently events with low probability; the joint probability of the two independent events, each with low probability, is extremely low and so is ignored. It can be introduced later if required; to do so it is necessary to know the rain-attenuation statistics at the IRIDIUM earth station sites, taking into account the multiple terminals of the IRIDIUM earth-station complex.

The interference equations in an downlink-interference situation are similar but slightly more complex. They are:

$$C = P_D - A_{CA} - A_{D.FS} + G_{DSC} + G_{DES} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(C.4)},$$

$$I = P_I - A_{CA} - A_{I.FS} + G_{ISC} + G_{DES} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(C.5)},$$

and

$$C/I = (P_D - P_I) + (G_{DSC} - G_{ISC}) + F_{BW} - (A_{D.FS} - A_{I.FS}) \ldots\ldots\ldots\ldots\ldots\ldots \text{(C.6)},$$

where most of the terms represent the same quantities as in the uplink equations, except that

$A_{D.FS}$ is the free-space-loss of the desired downlink signal, and

$A_{I.FS}$ is the free-space-loss of the interfering downlink signal.

These last two terms were identical in the uplink situation, but are very different in the downlink situation.

C.3 Evaluation of Interference Levels

C.3.1 Uplink Interference from the GSO SPACEWAY Earth Station Into the LEO IRIDIUM Satellite

The uplink interference from the SPACEWAY earth station into the IRIDIUM satellite is determined in Table C-1. In the analysis of this interference mode, the C/I at the IRIDIUM satellite receiver would be unacceptable if the IRIDIUM earth station power level were to be left at the -18.7 dBW level required at the 30° elevation angle without inter-network interference. However, the IRIDIUM earth station has the capability to raise the earth station power level over the range from -22.3 dBW to +12 dBW in the event that the uplink system's C/(N+I) level drops below acceptable levels. It is assumed that this APC servo system would respond rapidly to overcome the increasing interference, up to the limit of + 12 dBW.

As shown in Table C-1, the IRIDIUM Xmtr power level required would depend on the number of SPACEWAY earth station transmitters were operating in the small area covered by the IRIDIUM satellite antenna. This number might be anywhere from 1 to 13. In any case, the APC system in the IRIDIUM earth station could overcome the interference; *it is likely that it could and would do so.*

In conclusion, there would be no harmful interference into the IRIDIUM spacecraft, primarily due to the dynamic use of the APC in the IRIDIUM earth station. However, as seen below, this increase would simultaneously increase interference levels into the SPACEWAY satellite receiver.

C.3.2 Uplink Interference from LEO IRIDIUM the Earth Station Into the GSO SPACEWAY Satellite

The interference into the SPACEWAY satellite receiver is indicated in Table C-2. In this table the IRIDIUM earth station power is shown as a variable, from - 7.8 dBW to + 3.3 dBW. These levels, rather than the level - 18.7 required to overcome only thermal noise, is assumed to be used to overcome interference from the SPACEWAY earth station(s), as discussed in the previous section. The level in the - 7.8 dBW to + 3.3 dBW range would depend on how many SPACEWAY earth terminals were in operation in the uplink antenna beam of the IRIDIUM spacecraft. In any case, the worst-case C/I levels at the SPACEWAY satellite receiver would range from +3.3 dB to - 7.8 dB. Operation of the SPACEWAY system would not be possible in this environment; **the negative C/I margin ranges from - 3.6 dB to a worst-case -14.7 dB.**

It should be noted that these are the margins in the SPACEWAY satellite, and so prohibit operation in the interfered-with bands throughout the complete coverage area of the SPACEWAY uplink beam, not just in a small area near the IRIDIUM earth station.

C.3.3 Downlink Interference from the GSO SPACEWAY Satellite Into a LEO IRIDIUM Earth Station

The worst-case downlink interference from a SPACEWAY satellite into an IRIDIUM earth station is indicated in Table C-3. In determining these interference conditions Equations C-4 to C-6 are used, because the free-space losses are different for transmissions from the two satellites. For this interference mode the worst-case C / I at the IRIDIUM earth station receiver would be -9.6 dB if the APC in the IRIDIUM satellite did not respond to the increase in interference, ie. to a reduction in the downlink C / I. If it did so respond to the maximum output power of the satellite transmitter. it would increase its power level by 15.1 dB to the maximum - 3.2 dBW, resulting in a C / (N+I) of 5.5 dB, only 2.2 dB below its minimum operational level.

This operation of the IRIDIUM APC system in the presence of interference would, however, increase significantly the interference levels in the downlink SPACEWAY receiving earth stations, as indicated in the following section.

C.3.4 Downlink Interference from the LEO IRIDIUM Satellite Into a GSO SPACEWAY Earth Station

The same C-4 to C-6 equations are used to determine the worst-case interference from an IRIDIUM satellite into a SPACEWAY user terminal in the beam of the IRIDIUM downlink beam. Note that 384 kbps traffic is assumed in the SPACEWAY system. If the IRIDIUM system did not implement its APC system on its satellite to overcome interference from the SPACEWAY satellite into its earth terminal, the C/I at the SPACEWAY earth terminal would be an acceptable 10.2 dB. However, if or when the IRIDIUM satellite's APC system was used to the extent possible to overcome interference from the SPACEWAY satellite, the C / I level in the SPACEWAY user terminal would drop to - 4.9 dB, a level 8.8 dB below the minimum that could be accepted in the demodulator of the SPACEWAY user terminal. Assuming that the IRIDIUM system would use its APC to the maximum extent possible, it must be assumed that the worst-case C / I in the SPACEWAY user terminals would be 8.8 dB below the minimum acceptable level.

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Table C-1

**Uplink Interference Into the IRIDIUM Satellite Receiver
From One or More SPACEWAY Earth Stations**

Parameter	Detailed Consideration	Contribution to C/I Ratio		
Initial Iriduim ES Power P_D, dBW	-18.7	-18.7		
Spaceway ES Power P_I, dBW	-3.5	+ 3.5		
Iridium ES Antenna Gain, dBi	56.3	+ 56.3		
Spaceway ES Antenna Gain, dBi	44.3	- 44.3		
Bandwidth of Iridium Signal, MHz	6.25			
Channel Size of Spaceway Signal, MHz	0.500			
Log of No. of Interfering GSO Signals	Max of 13, or 11.1 dB *	0	- 3	- 11.1
Worst-Case C/I		-3.2	-6.2	- 14.3
Required Increase in LEO Power #		10.9	13.9	22.0
Modified Iriduim ES Power P_D, dBW to achieve a C/(N+I) of 7.7 dB		- 7.8	- 4.8	+ 3.3

*   This 11.1 dB reduction in C/I at the IRIDIUM spacecraft due to multiple SPACEWAY carriers in the IRIDIUM spacecraft antenna beam is a worst-case value. It assumes that the 6.25 MHz band is saturated by FDMA uplinks from SPACEWAY Earth terminals, all of them in the small area illuminated by the 5° beam from the IRIDIUM spacecraft. Since the SPACEWAY uplink beam covers a much larger area than the IRIDIUM antenna, this is a very pessimistic number; a more likely number would be 1 or 2 SPACEWAY terminals in operation in the IRIDIUM beam, ie. the F_{BW} factor would more likely be 0 dB or - 3 dB rather than the maximum - 11.1 dB.

\#   A total of 30.7 dB of additional APC-controlled power is available to overcome the reduction in power caused by interference from the SPACEWAY earth-station transmissions. The maximum increase required is 22 dB, but a considerably smaller increase is likely required.

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Table C-2

Uplink Interference Into the SPACEWAY Satellite Receiver From an IRIDIUM Earth Station with its APC In Operation

Parameter	Detailed Consideration	Contribution to C/I Ratio
Spaceway ES Power P_D, dBW	-3.5	-3.5
Iridium ES Power P_I, dBW	- 4.8 to + 6.3 *	+ 4.8 to - 6.3 *
Spaceway ES Antenna Gain, dBi	44.3	+ 44.3
Iridium ES Antenna Gain, dBi	56.3	- 56.3
Bandwidth of Spaceway Signal, MHz	0.500	.
Bandwidth of Iridium Signal, MHz	6.25	
Bandwidth Factor, dB	10.97	+ 10.97
Worst-Case C / I levels		+ 3.3 to -7.8 *
Margin below Req'd 6.9 dB, in dB		3.6 to 14.7

* The range is dependent on the increase in power that the IRIDIUM earth station implements to control the C / (N+I) level in its satellite. An increase in the APC-controlled IRIDIUM earth station will simultaneously increase the interference level in the SPACEWAY satellite, because the bursts of interference, if they occur, will occur in both !ites at the same time, the time that an earth station of either network is roughly in line w.... both satellites.

Table C-3

Downlink Interference Into an IRIDIUM Earth Station Receiver
From a SPACEWAY Satellite

Parameter	Detailed Consideration	Contribution to C/I Ratio
Initial Iriduim Sat. Power P_D, dBW	-18.3	-18.3
Spaceway Sat. Power P_I, dBW	+12.5	- 12.5
Iridium Sat. Antenna Gain, dBi	26.9	+ 26.9
Spaceway Sat. Antenna Gain, dBi	46.5	- 46.5
Bandwidth of Iridium Signal, MHz	6.25	
Bandwidth of Spaceway Signal, MHz	120	
Bandwidth Factor, dB	12.83	+ 12.83
Free-Space Loss, IRIDIUM	182.2	- 182.2
Free-Space Loss, SPACEWAY	210.2	+ 210.2
Initial Worst-Case C/I, dB		-9.6
Increase in Satellite Power Available, dB		15.1
Worst-Case C/I after correction, dB		5.5
C / (N+I) after correction, dB		5.5
Margin below Req'd 7.7 dB, dB		2.2